Monte Carlo Simulations for Space Experiments and Possible Application to Con-X

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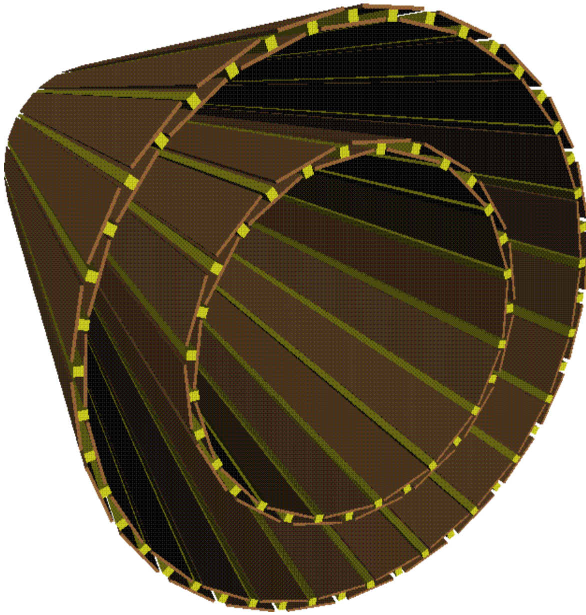
Outline of Talk

- **Introduction**
  - GLAST
- **GEANT4**
  - Overview
  - Geometry
  - EM Physics Processes
  - Hadronic Physics Processes.
- **Utilization of GEANT4**
  - XMM
  - Possible uses for CON-X

NB: Much of the GEANT4 background material taken from talk of John Apostolakis, CERN

(for the Geant4 collaboration)



GLAST Large Area Telescope (LAT)

~200 "collaborators"

Si Tracker Tower

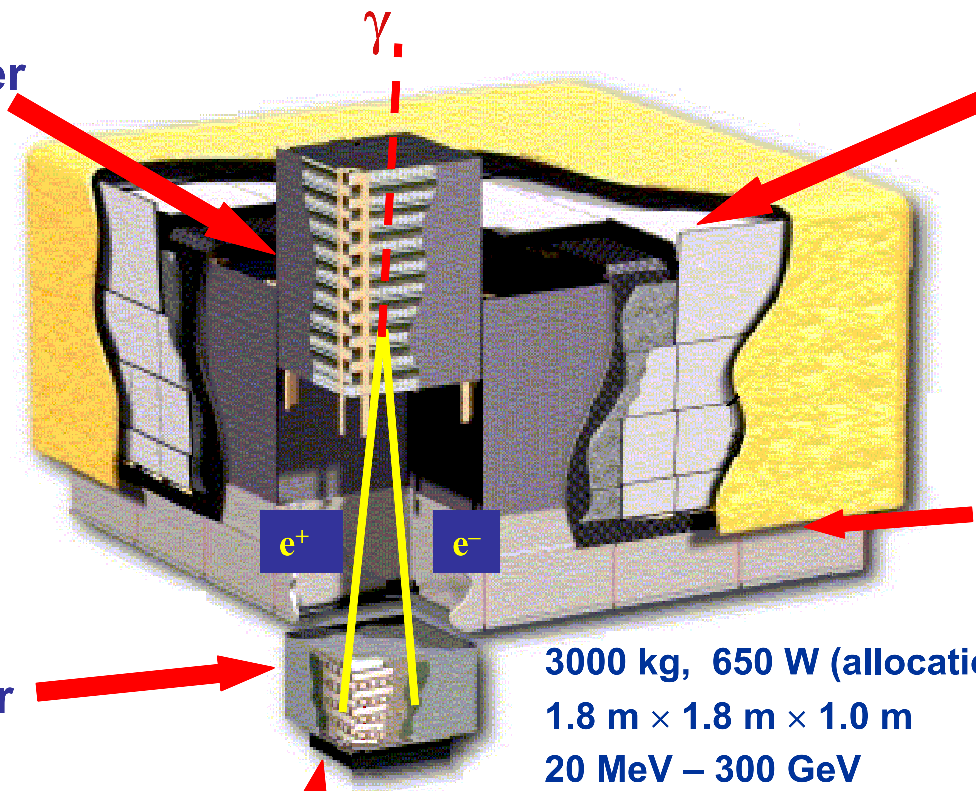
pitch = 228 µm

5.52 10^4 channels

12 layers × 3% X_0

+ 4 layers × 18% X_0

+ 2 layers



ACD

Segmented scintillator tiles

0.9997 efficiency

⇒ minimize self-veto

Grid (& Thermal Radiators)

CsI Calorimeter

Hodoscopic array

8.4 X_0 8 × 12 bars

2.0 × 2.7 × 33.6 cm

⇒ cosmic-ray rejection

⇒ shower leakage correction

3000 kg, 650 W (allocation)

1.8 m × 1.8 m × 1.0 m

20 MeV – 300 GeV

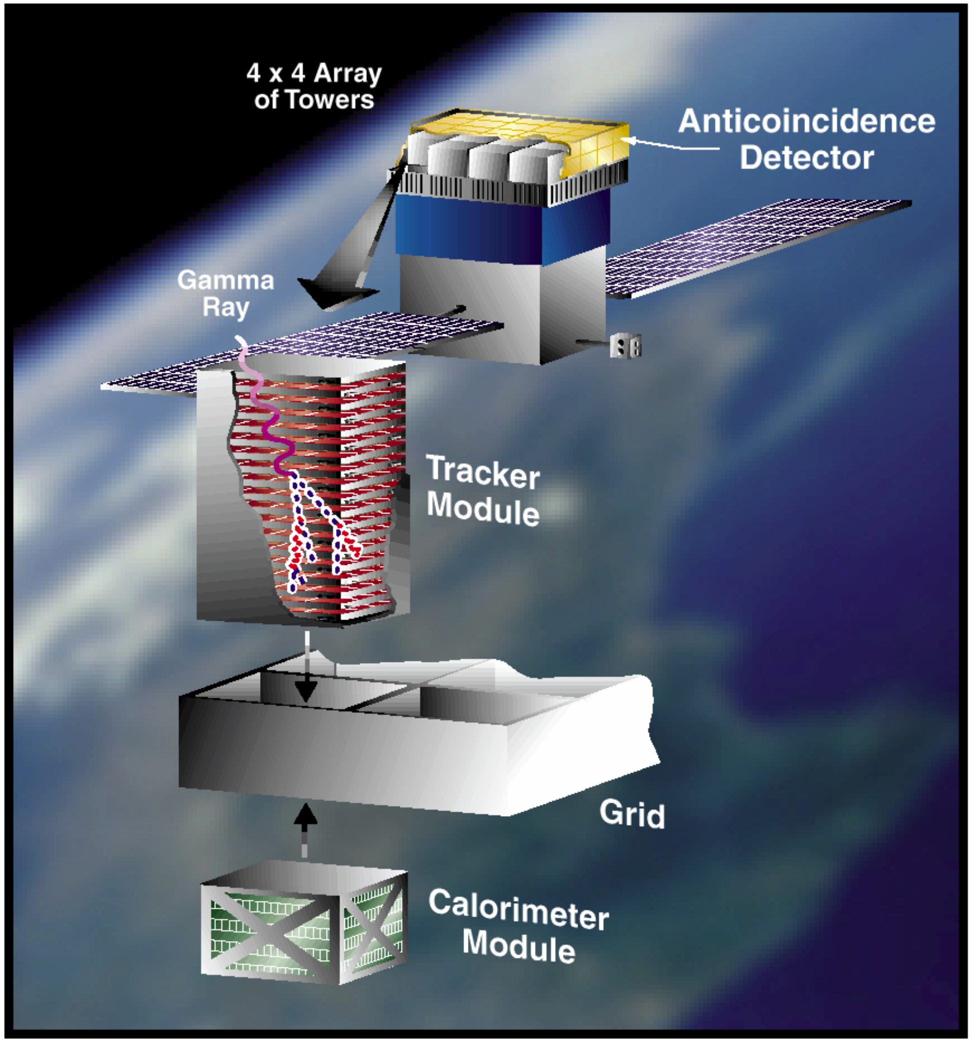
Data acquisition

The Instrument will be integrated at SLAC. It will be tested at SLAC and NRL ("environmental tests")

Monte Carlo simulation started at SLAC in 1992 (Atwood, et al). Science Analysis Software subsystem is currently lead by Richard Dubois of SLAC.

Overview of LAT

- <u>7x7 →4x4 array of identical towers</u> Advantages of modular design.
- <u>Precision Si-strip Tracker (TKR)</u> Detectors and converters arranged in 18 X-Y tracking planes. Measure the photon direction. (extensive development via M.C.- strip pitch)
- <u>Hodoscopic CsI Calorimeter(CAL)</u> Segmented array of CsI (Tl) crystals. Measure the photon energy. (Major M.C. contribution to design.)
- <u>Segmented Anticoincidence Detector (ACD)</u> First step in reducing the large background of charged cosmic rays. Segmentation removes self-veto effects at high energy. (Justified via M.C.)
- <u>Electronics System</u> Includes flexible, highly-efficient, multi-level trigger. (Modeled in M.C.)

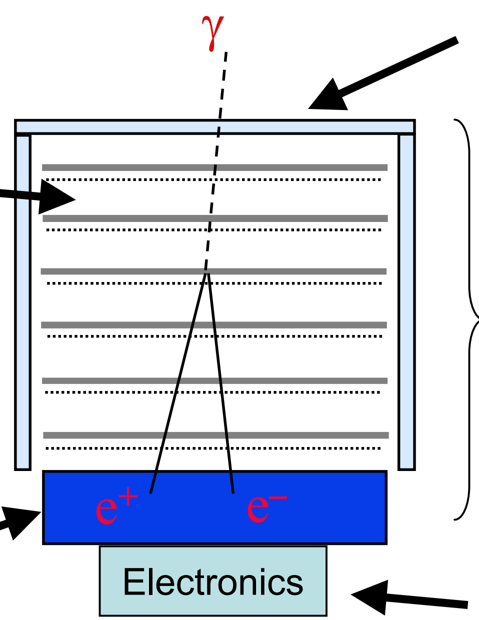


<u>Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV →300 GeV.</u>

Science Drivers on Instrument Design

Effective area and PSF requirements drive the converter thicknesses and layout. PSF requirements also drive the sensor performance, layer spacings, and drive the design of the mechanical supports.

Background rejection requirements drive the ACD design (and influence the calorimeter and tracker layouts).



Field of view sets the aspect ratio (height/width)

Energy range and energy resolution requirements bound the thickness of calorimeter

Time accuracy provided by electronics and intrinsic resolution of the sensors.

On-board transient detection requirements, and on-board background rejection to meet telemetry requirements, are relevant to the electronics, processing, flight software, and trigger design.

Instrument life has an impact on detector technology choices.
Derived requirements (source location determination and point source sensitivity) are a result of the overall system performance.

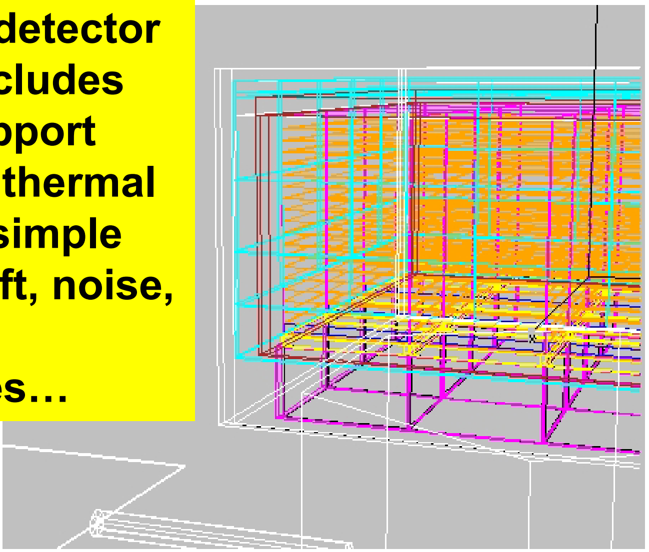
Design Performance Validation: LAT Monte-Carlo Model

The LAT design is based on detailed Monte Carlo simulations. An Integral part of the project from the start:

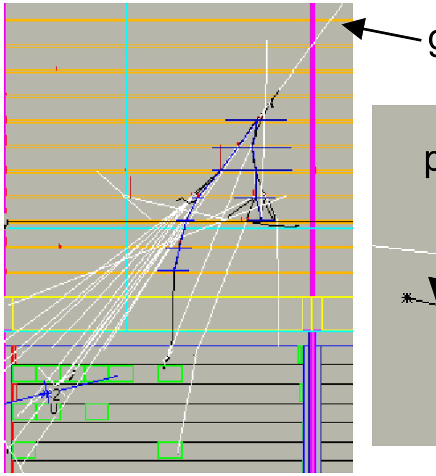
- **Background rejection**
- **Calculate effective area and resolutions (computer models now verified by beam tests). Current reconstruction algorithms are existence proofs -- many further improvements under development.**
- **Trigger design.**
- **Overall design optimization.**

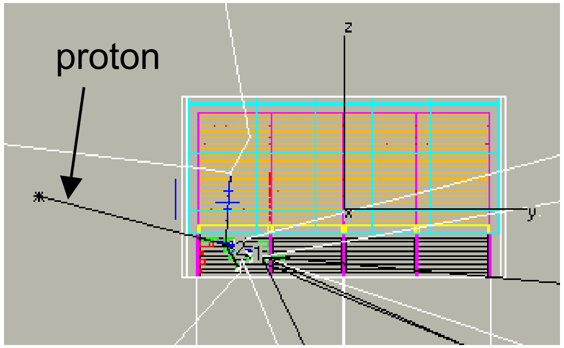
Simulations and analyses are all C++, based on standard HEP packages **(recently transitioned to GEANT4).**

Detailed detector model includes gaps, support material, thermal blanket, simple spacecraft, noise, sensor responses…



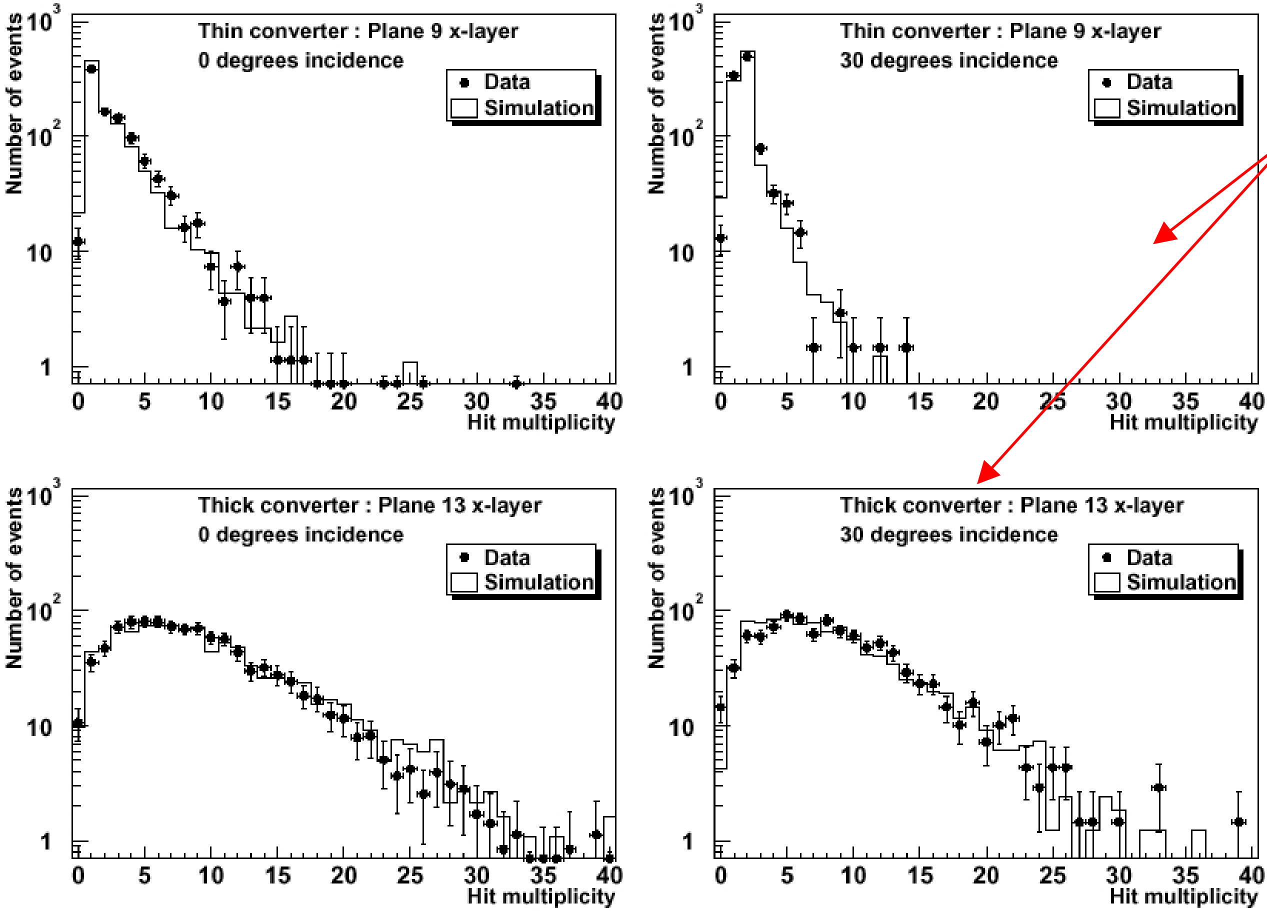
Instrument naturally distinguishes gammas from backgrounds, but details matter.





1999-2000 Beam Test at SLAC verified M.C. Modeling and Basic Instrument Design

Using beams of positrons, tagged photons and hadrons, with a ~flight-size tower, studies of:

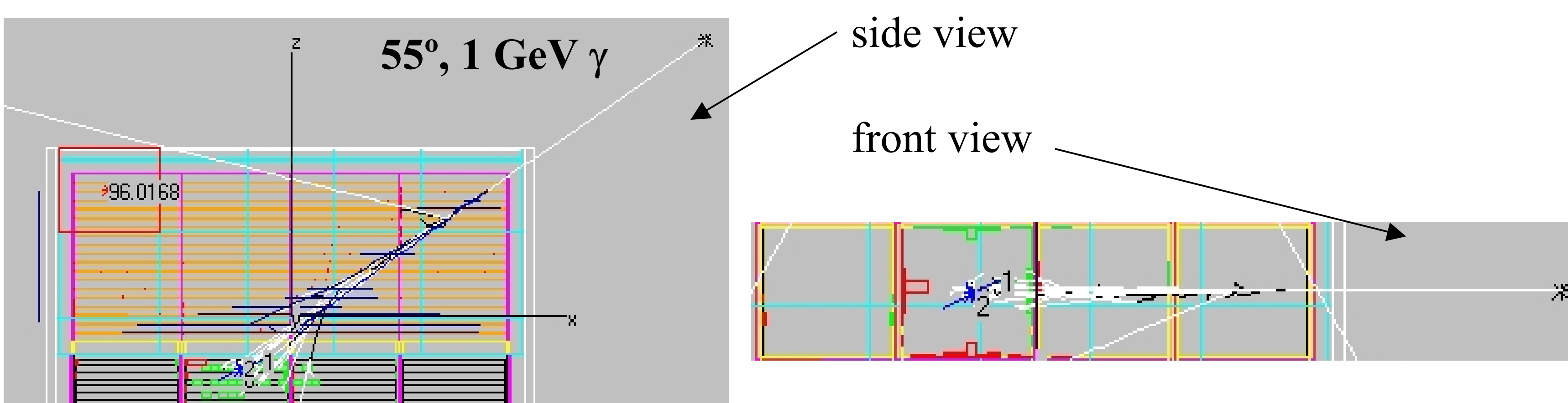


- data system, trigger.
- hit multiplicities in front and back tracker sections.
- calorimeter response with prototype electronics.
- time-over-threshold in silicon.
- upper limit on neutron component of ACD backsplash.
- hadron tagging and first look at response.

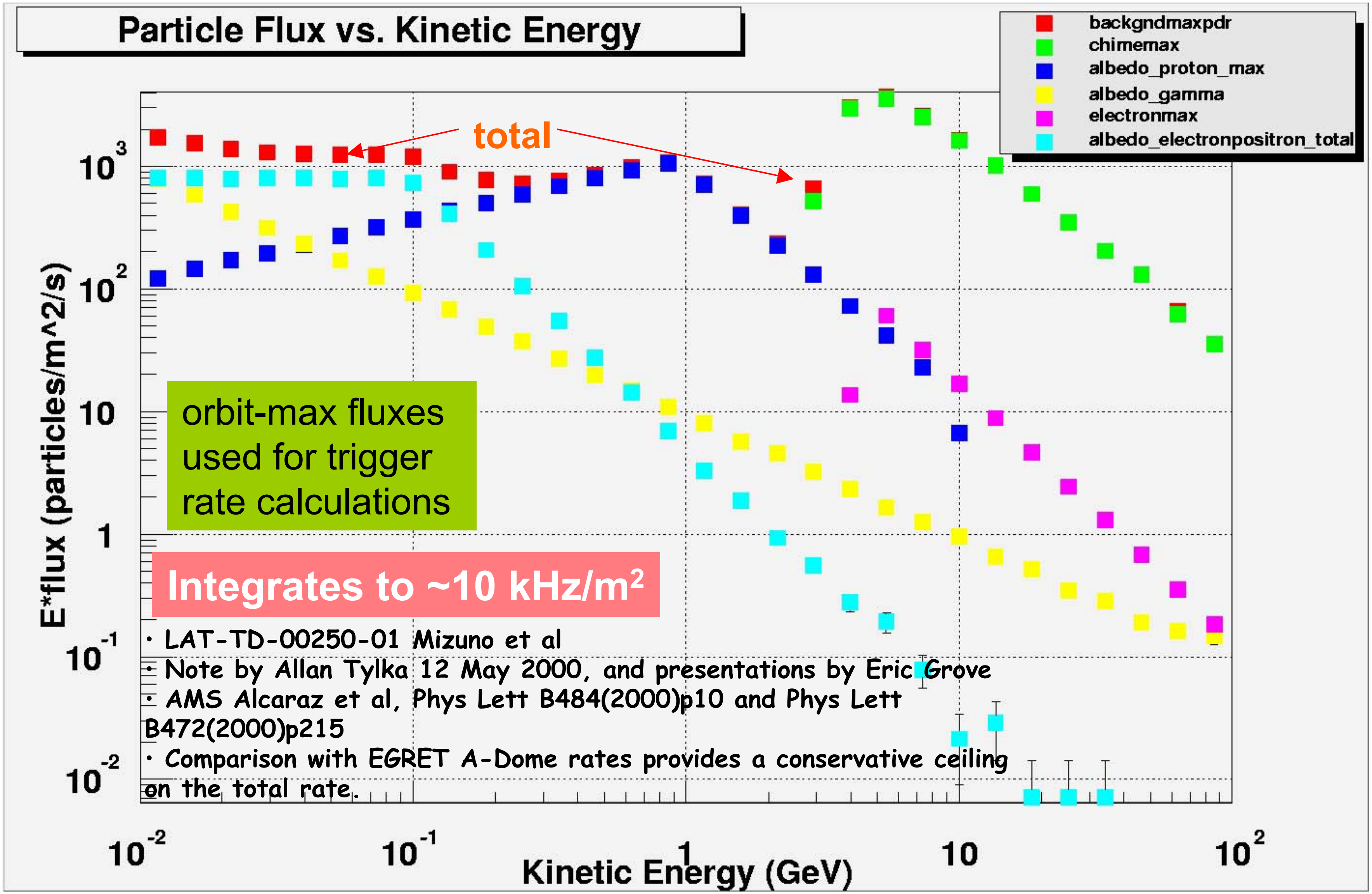
Published in NIM A474(2001)19.

Calibration Strategy

- Every LAT science performance requirement has a draft defined test.
- LAT energy range and FOV are vast. Testing will consist of a combination of simulations, beam tests, and cosmic ray induced ground-level muon tests. It is neither practical nor necessary to verify the full range of LAT performance space by **<u>direct tests of the full Lat</u>**. Instead, the beam tests are used to sample the performance space on a subset of the modules and to verify the detailed simulation; analysis using the simulation is used to verify the full range of performance parameters.
- With this strategy, every LAT science performance requirement can be verified. All the science performance requirements can be verified in beam tests using four towers. Full-LAT tests are <u>functional</u> tests.

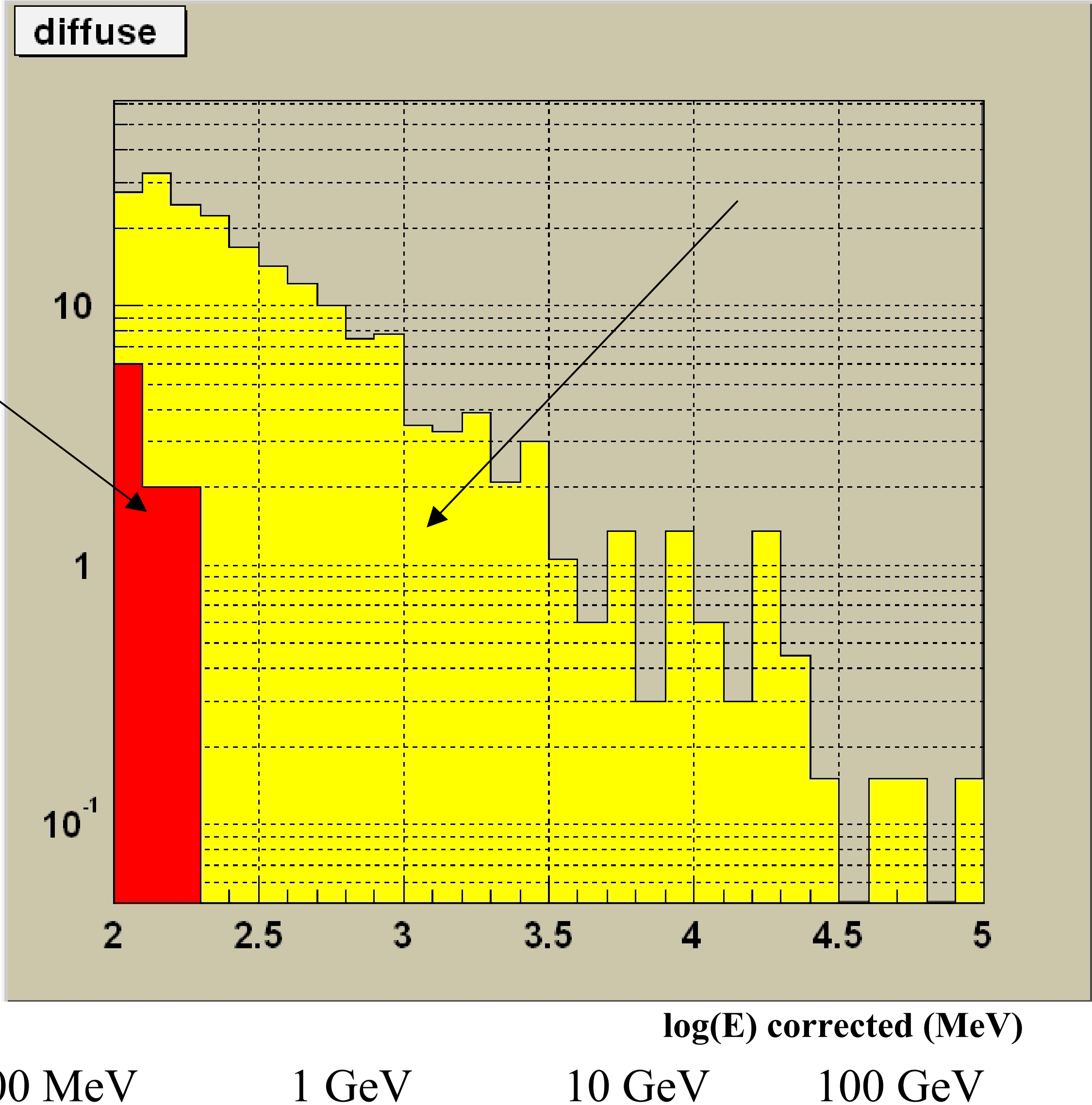


Implemented On-Orbit Background Fluxes



Background Rejection Results (M.C.)

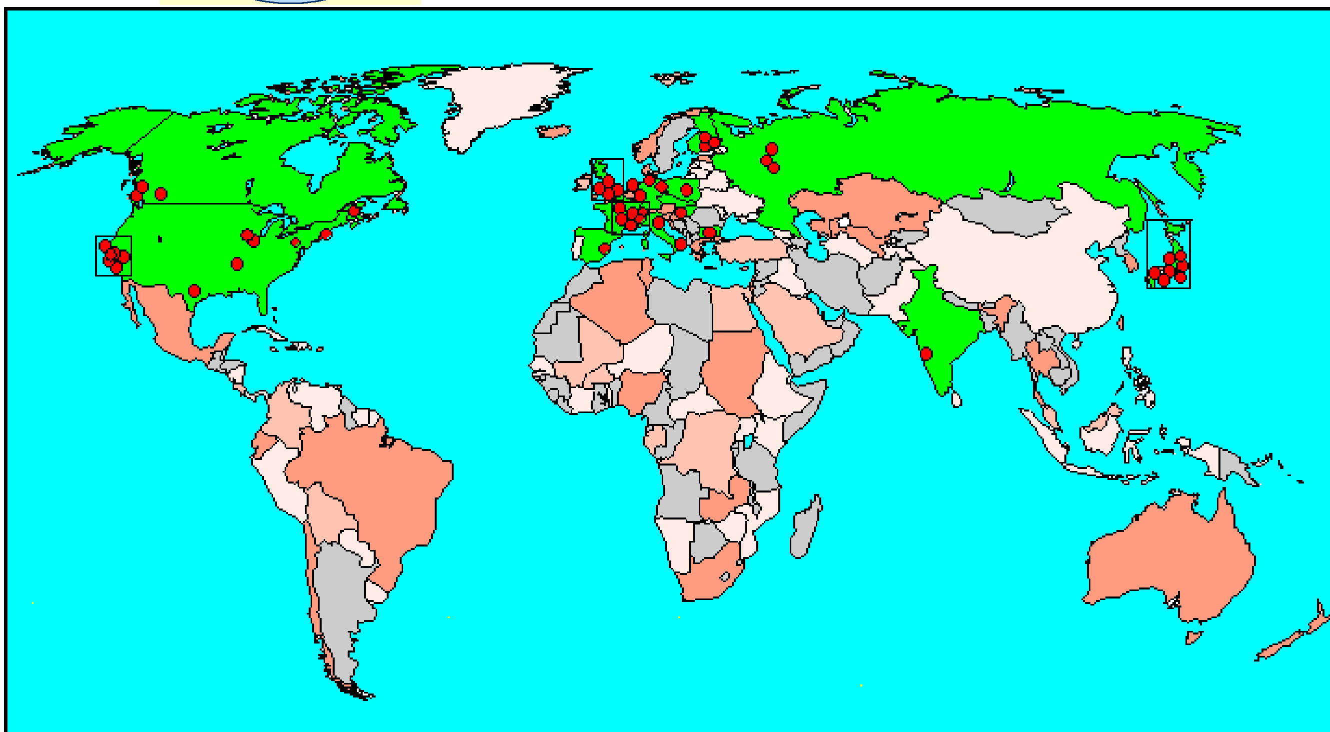
- Requirement: <10% contamination of the measured extragalactic diffuse flux for E>100 MeV
- Residual background is 5% of the diffuse (6% in the interval between 100 MeV and 1 GeV). Important experimental handle: large variation of background fluxes over orbit – compare diffuse results over orbit.
- Below 100 MeV [no requirement], without any tuning of cuts for low energy, fraction rises to 14%. This will improve.
- Peak effective area: 10,000 cm^2 (at ~10 GeV).
- Effective area at 300 GeV: 8,000-10,000 cm^2, depending on analysis selections.



GEANT4 Overview

- Originally a Detector simulation tool-kit for HEP
  - offers alternatives, allows for tailoring
- Software Engineering and OO technology
  - provide the method for building, maintaining it.
- Requirements from:
  - LHC
  - heavy ions, CP violation, cosmic rays
  - medical and space science applications
- World-wide collaboration

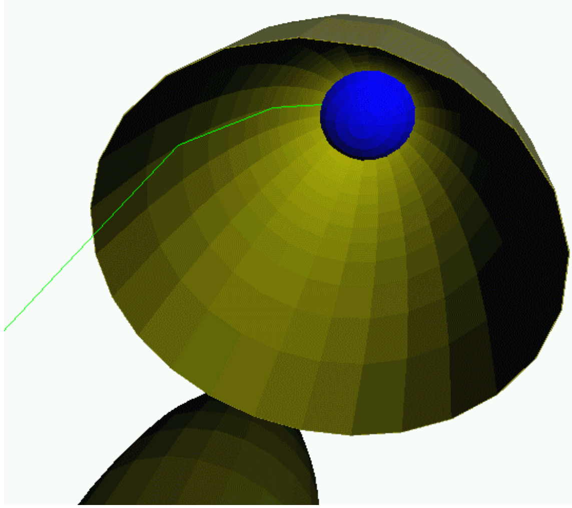
GEANT4 Collaboration



Collaborators also from non-member institutions, including
Budker Inst. of Physics, IHEP Protvino,
MEPHI Moscow, Pittsburg University

GEANT4 Capabilities

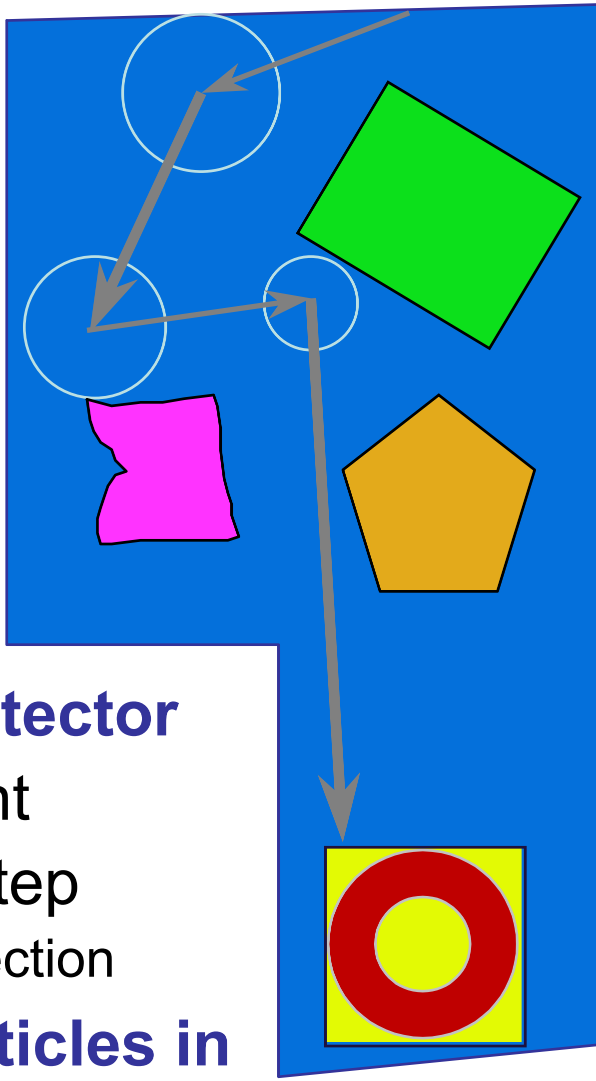
- Powerful structure and kernel
  - tracking, stacks, geometry, hits, …
- Extensive & transparent physics models
  - electromagnetic, hadronic, …
- Framework for fast simulation
- Additional capabilities/interfaces
  - persistency, visualization, ...



GEANT4 geometry: what it does

Describes a Detector

- Hierarchy of volumes
- Many volumes repeat
  - Volume & sub-tree
- Up to millions of volumes for LHC era
- Import detectors from CAD systems



Navigates in Detector

- Locates a point
- Computes a step
  - Linear intersection

Propagates Particles in E-M Fields

Electromagnetic physics

- Gammas:
  - Gamma-conversion, Compton scattering, Photo-electric effect
- Leptons(e, μ), charged hadrons, ions
  - Energy loss (Ionization, Bremsstrahlung) or PAI model energy loss, Multiple scattering, Transition radiation, Synchrotron radiation,
- Photons:
  - Cherenkov, Raleigh, Reflection, Refraction, Absorption, Scintillation
- High energy muons and lepton-hadron interactions
- Alternative implementation (“low energy”)
  - for applications that need to go below 1 KeV
  - Down to 250eV (e+/γ), O(0.1) μm for hadrons

Hadronic processes

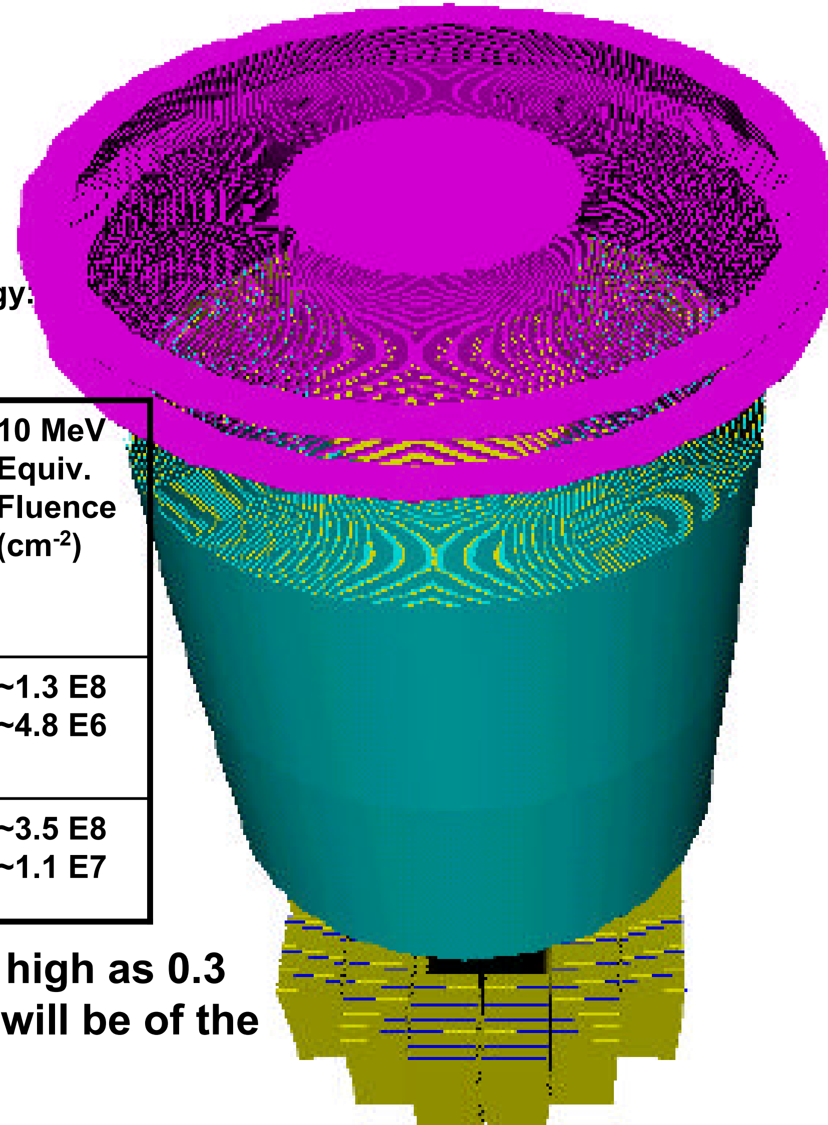
- **3 types of models and cross-sections**
  - for each energy regime, particle type, material
  - alternatives with different strengths and computing resource requirements
- **Five level implementation framework**
  - allows models to be used in combination at different levels
    - Solving the mix and match problem in the framework
- **Model types:**

1. **Data driven approach**
   - Neutrons
     - from numerous evaluated data libraries
     - down to thermal energies, up to 20 MeV
   - Isotope production (see next slide)
   - Induced Fission & Capture (H.Fesefeldt)
     - used above 20 MeV
   - Photon-evaporation, radioactive decay, etc.
2. **Parameterized models**
   - Geisha + fixes + new parameterizations (H.F, TRIUMF)
3. **Theoretical models, from low E to high E**
   - Pre-Compound Model + Evaporation Phase
   - Cascades, CHIPS and QMD models
   - String models
     - Excitation, fragmentation, hadronization models

The Use of GEANT4 in XMM
E. Daley et al, ESA, DERA, CERN, INFN

- Low energy proton problem
- modeling in ESTEC (TRIM, GEANT4,…)
- validation attempts
- environment assessment (then)
- environment (recent)

GEANT4 Model of XMM



Q(E) = scattering from a single encounter with a shell (either a single scatter of a "condensed“ multiple scatter)-- a strong function of energy.
S = telescope acceptance area.
f **= omni directional flux of particles, differential in energy.**

Accep. Area- S (cm^2)	Accep. Angle (Sr)	L (cm)	E (MeV)	Fluence interval (f(E)DE) (cm^{-2})	Q(E)	Fluence (cm^{-2}) $Q(E)^2 * f(E)dE * S / 4\pi L^2$	10 MeV Equiv. Fluence (cm^{-2})
Chandra 1145	1E-4	1E3	0.1	>1E13	0.065	~1.3 E6 ~4.8E5	~1.3 E8 ~4.8 E6
XMM 1700	6.5E-5	7E2	0.1	>2E13	0.065	~3.5 E6 ~1.1 E6	~3.5 E8 ~1.1 E7

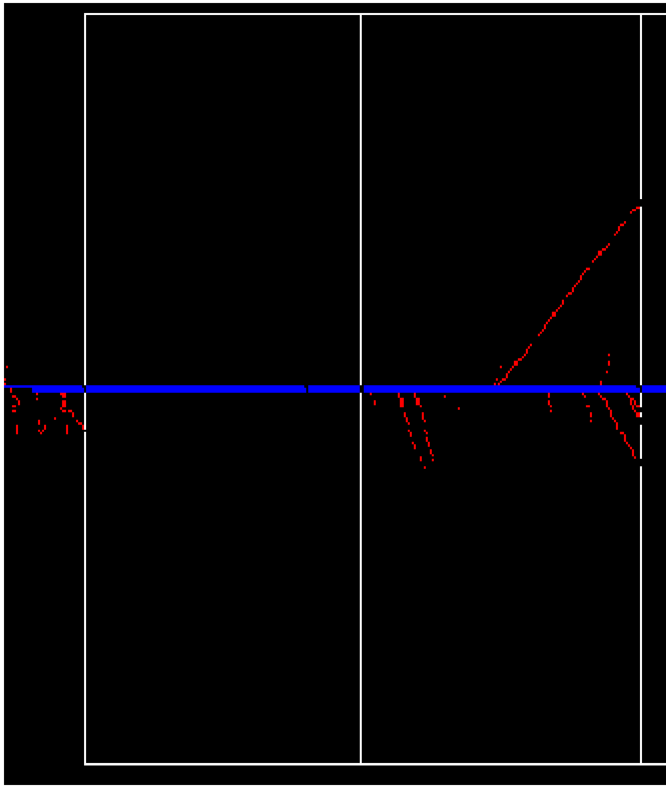
Fluence values in Table are lower bounds; if Q is as high as 0.3 the 10 MeV equivalent fluence from 100keV protons will be of the order of 1E10 cm^{-2} in 60 days at the CCDs.

Possible uses for CON-X

- **M.C simulations have clearly proven to be of great value to other space experiments – GLAST, Integral, XMM. All use GEANT4 and are part of the GEANT4 Collaboration.**
- **For Con-X GEANT4 Can be very useful for a Number of Purposes:**.
  - **Overall optimization of the telescope including sensitivity, background in the context of various spacecraft/instrument design tradeoffs.**
  - **Evaluation of the Particle Backgrounds and Particle Induced X-ray Backgrounds**.
    - Con-X will employ very sensitive sensors, and thus reducing the instrumental background to a minimum will be essential for studies of faint sources.
    - Given the particle environment (energy spectrum, direction wrt the spacecraft, …) one can estimate the flux at the sensors and thus perform optimization and trade studies of the spacecraft structure, detector locations, and possible shielding, etc.
    - By simulating the materials content of the spacecraft/instruments, one can evaluate the energy spectrum at the sensor (and its time dependence after an exposure to the given dose) of X-rays/gamma-rays resulting from activation.
  - **Evaluation of the X-ray Detectors' Redistribution Matrix**.
    - Current "baseline" sensors are cryogenic micro-calorimeters that rely on the measurement of temperature change in the thermometers resulting from the absorption of an X-ray. In an idealized device that is ideally packaged, 100% of the energy goes into heat, but there may be other potential "branches".
    - Monte Carlo simulations, where all know physical interactions are included, can aid in determining the real redistribution matrix.

EXTRA Slides

Electromagnetic processes



Processes included in Geant4

- Multiple Scattering: new model
  - includes lateral displacement
  - no path length restriction
- Transition radiation
  - from physics models
- Photo-Absorption Ionization model
  - Alternative energy loss referred to as PAI model

(Recently Checked by NRL for low energy electron backscattering-ref, and agreement was marginal (x2). Work is still needed,)

Backscattering of Low Energy Electrons:

Testing GEANT4 - E. Novikova, George Mason U. / NRL

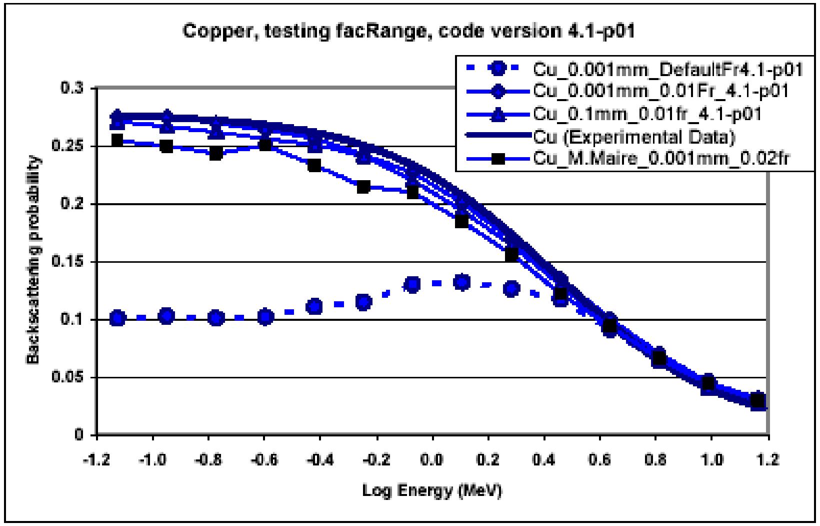


Figure 3. Comparison of the simulation data for copper to the experimental data of Tabata et.al.

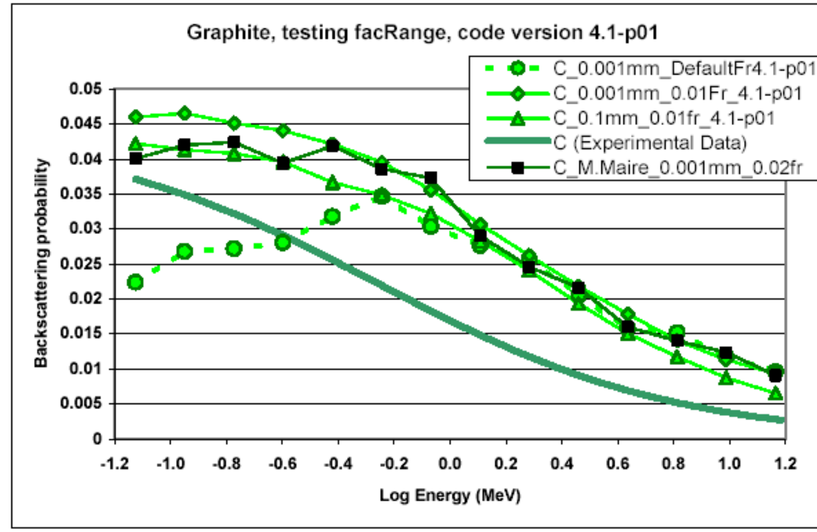


Figure 9. Comparison of the simulation data for graphite to the experimental data of Tabata et.al.

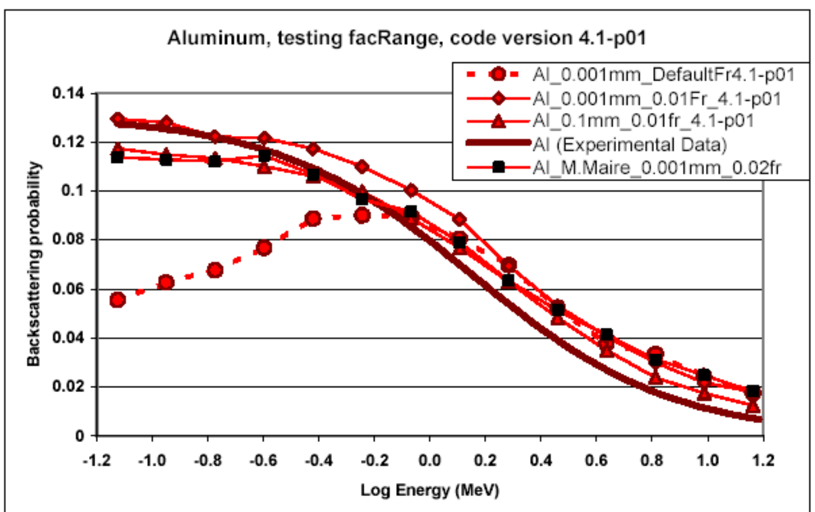


Figure 4. Comparison of the simulation data for aluminum to the experimental data of Tabata et.al.

The agreement between the simulation and the experimental data for copper is very good. Results for aluminum are not that stellar: for the energies around 10 MeV the discrepancy reaches 50% or so. The results for graphite are worse: the results of the simulation exceed the experimental data by a factor of two over the whole range of energies. In general, the simulation data has a tendency of overestimating the backscattering coefficient for small Z and slightly underestimating it for larger Z.